CLAIMS

What is claimed is:

1. 1. A method of seismic surveying using vibrational seismic energy sources

2. activated by sweep signals, the method comprising:

3. (a) selecting a plurality of seismic energy sources to be used for surveying

4. and a second number of sweep segments in excess of said first plurality;

5. (b) selecting a third plurality of a highest order harmonic to be attenuated

6. from processed data acquired using said seismic sources;

7. (c) defining a sweep signal associated with each of said sources, each sweep

8. signal comprising a plurality of sweep segments, each sweep segment of

9. each seismic source having a determined phase;

10. (d) driving each said source with its associated sweep signal to generate

11. seismic waves propagating into the earth and recording a seismic signal in

12. response thereto; and

13. (e) processing said recorded seismic signal using a plurality of augmented

14. signals associated with each seismic source to produce a processed

15. plurality of processed seismic signals, each of said plurality of processed

16. seismic signals associated with a different one of said seismic sources and

17. having harmonics upto said selected third plurality attenuated.

1. 2. The method of claim 1 further comprising determining said phase for each said

2. segment of each said sweep signal, wherein said phase is determined by

3   (i)   constructing a table with N rows and N columns, where N is the plurality

4   of sweep segments, each entry $e_{H,M}$ being calculated from the formula

5            $e_{H,M} = hm$ modulo N,

6   where h is the row number and m is the column number;

7   (ii)   selecting a number of columns equal to the number of sources such

8   that the number in the first row of each selected column does not appear

9   again in any selected column before the row H=F+1, where F is the

10   highest order harmonic determined to cause significant crossfeed;

11   (iii)   assigning a selected column to each seismic energy source, the initial

12   phase angle for the hth sweep of that seismic energy source being

13   represented by the number in the hth row of that column multiplied by

14           $2\pi/N$;

1   3.   The method of claim 1 wherein each said associated sweep signal comprises

2   sweep segments, said sweep segments either concatenated or overlapping

3   sequentially.

1   4.   The method of claim 3 wherein each said augmented sweep signal further

2   comprises said associated sweep signal and at least one of (i) a first sweep

3   segment of said associated sequence, and, (ii) a final segment of said associated

4   sequence.

1   5.   The method of claim 1 further comprising measuring a level of the generated

2   seismic signal and using said level to adjust an amplitude of each of said other of

3   said augmented signals prior to correlating said recorded seismic data.

1   6.   The method of claim 1, wherein said sweep segments further comprise a

2   sinusoidal wavetrain having a frequency that either increases monotonically with

3   time or decreases monotonically with time.

1   7.   The method of claim 6 wherein said increase or decrease of said frequency is

2   linear with time.

1   8.   The method of claim 1, wherein said sweep segments further comprise a psuedo-

2   random sweep series.

1   9.   The method of claim 8, wherein said pseudo-random sweep series are phase-

2   rotated by selected increments.

1   10.   A method for recording and processing vibratory source seismic data, the method

2   comprising:

3   (a)   generating a cascaded sweep sequence comprising N sweep segments

4   that are either concatenated or overlapping sequentially, where N is equal

5   to or greater than 2, said N sweep segments being substantially identical,

6   except that the initial phase angles of said N sweep segments are

7   progressively rotated by a constant phase increment of about $2\,m\pi/N$

8   radians where m is an integer and $|m|>1$;

9   (b)   using said cascaded sweep sequence to drive a vibratory source thereby

10   propagating a seismic wave into the earth at a selected location;

11   (c)   recording a groundforce signal associated with said seismic wave,

12   (d)   recording at least one reflection signal from a location within the earth

13   responsive to said seismic wave, and

14   (e)   using said recorded groundforce signal for processing the signal recorded

15   to produce a processed signal.

1   11.   The method of claim 10 wherein processing the signal recorded comprises cross-

2   correlating the recorded signal with a signal comprising said groundforce signal

3   and a first and a last sweep segment of said groundforce signal.

1   12.   The method of claim 10, wherein said sweep segments further comprise a

2   sinusoidal wavetrain having a frequency that either increases monotonically with

3   time or decreases monotonically with time.

1   13.   The method of claim 12 wherein said increase or decrease of said frequency is

2   linear with time.

1   14.   The method of claim 10, wherein said sweep segments further comprise a psuedo-

2   random sweep series.

1   15.   A method of seismic surveying using n vibrational seismic energy sources

2   activated by sweep signals, the method comprising:

3   (a)   selecting a number of seismic energy sources to be used for surveying;

4   (b)   selecting a number of a highest order harmonic that has sufficient strength

5   to cause significant harmonic distortion of a sweep segment that is part of

6   a sweep sequence;

7   (c)   defining a reference signal associated with each of said sources, each

8   reference signal comprising a number N of sweep segments, N being

9   greater than n, said sweep segments being either concatenated or

10   overlapping;

11   (d)   selecting initial phase angles for each sweep segment of each reference

12   signal so that substantially all harmonics up to and including said highest

13   order harmonic are suppressed and driving each vibratory source with its

14   sweep sequence and driving each of said sources with its associated

15   reference signal, thereby generating seismic waves propagating into the

16   earth;

17   (e)   recording ground force signals associated with each reference signal;

18   (f)   recording at least one reflection signal from a location within the earth

19   responsive to said seismic waves;

20   (g)   using said n ground force signals for processing said at least one recorded

21   reflection signal.

1   16.   The method of claim 15 wherein processing said at least one recorded signal

2 comprises correlating the at least one recorded signal with a plurality of

3 processing signals, each said processing signal comprising a reference signal

4 combined with at least two segments of the reference signal.

1 17. The method of claim 15 wherein selecting initial phase angles further comprises:

2 (i) constructing a table with N rows and N columns, each entry e_{hm} being

3 calculated from the formula $e_{hm} = h\, m$ modulo (N) where h is the row

4 number and m is the column number;

5 (ii) selecting a number of columns equal to the number of sources such that

6 none of the numbers of each selected column appears again in any other

7 selected column before the row $H = F+1$, and

8 (iii) assigning a selected column to each seismic energy source, the

9 initial phase angle for the h-th sweep segment of that seismic energy

10 source being represented by the number in the h-th row of that column

11 multiplied by $2\,\pi/N$.

1 18. The method of claim 15, wherein said sweep segments further comprise a

2 sinusoidal wavetrain having a frequency that either increases monotonically with

3 time or decreases monotonically with time.

1 19. The method of claim 18 wherein said increase or decrease of said frequency is

2 linear with time.

1   20.   The method of claim 15, wherein said sweep segments further comprise a psuedo-

2   random sweep series.

1   21.   The method of claim 20, wherein said pseudo-random sweep series are phase-

2   rotated by selected increments.

1   22.   A method of conducting n seismic surveys simultaneously at substantially the

2   same location where n is an integer, the method comprising:

3   (a)   simultaneously transmitting with n vibratory sources associated

4   groundforce signals into the earth, each said groundforce signal including

5   a fundamental signal and harmonics thereof, said fundamental signal

6   having an initial phase;

7   (b)   recording said n groundforce signals;

8   (c)   recording at least one reflection signal from a location within the earth

9   responsive to said plurality of groundforce signals to give a first recorded

10   signal;

11   (d)   repeating steps (a) - (c) m-1 times wherein said initial phases are shifted

12   by $2\pi/m$ radians to give a total of m recorded signals and $n \times m$

13   groundforce signals;

14   (e)   using the $n \times m$ ground force signals for processing the m recorded signals

15   to give processed signals associated with each vibratory source.

1   23.   The method of claim 22 wherein processing the m recorded signals further

2   comprises:

3   (i)   correlating the first recorded signal with each of the associated ground

4   force signal to give n intermediate signals;

5   (ii)   repeating step (i) m-1 times to give a total of n x m intermediate processed

6   signals;

7   (iii)   summing the m intermediate processed signals associated with each

8   vibratory source to give a processed signal associated with each vibratory

9   source.

1   24.   The method of claim 23, wherein said sweep segments further comprise a

2   sinusoidal wavetrain having a frequency that either increases monotonically with

3   time or decreases monotonically with time.

1   25.   The method of claim 24 wherein said increase or decrease of said frequency is

2   linear with time.

1   26.   The method of claim 22, wherein said sweep segments further comprise a psuedo-

2   random sweep series.

1   27.   A method of seismic surveying using vibrational seismic energy sources

2   activated by sweep signals, the method comprising:

3   (a)   selecting a number of seismic energy sources to be used for surveying;

4   (b)   selecting a number of a highest order harmonic that has sufficient strength

5   to cause significant harmonic distortion of a sweep segment that is part of

6   a sweep sequence;

7   (c)   selecting a number of sweep segments in excess of the number of seismic

8   energy sources used;

9   (d)   selecting initial phase angles for each sweep segment of each seismic

10   energy source so that substantially all harmonics up to and including said

11   highest order harmonic are suppressed, the step of selecting initial phase

12   angles further comprising:

13   (i)   constructing a table with N rows and N columns, where N is the

14   number of sweep segments, each entry $e_{H,M}$ being calculated from

15   the formula

16                     $e_{H,M} = hm$ modulo N,

17   where h is the row number and m is the column number;

18   (ii)   selecting a number of columns equal to the number of sources such

19   that the number in the first row of each selected column does not

20   appear again in any selected column before the row H=F+1, where

21   F is the highest order harmonic determined to cause significant

22   crossfeed;

23   (iii)   assigning a selected column to each seismic energy source, the

24   initial phase angle for the hth sweep of that seismic energy source

25   being represented by the number in the hth row of that column

26   multiplied by $2\pi/N$;

27   (e)   generating a first sweep sequence associated with each energy source,

28   consisting of sweep segments having initial phase angles obtained in step

29   (d), said sweep segments being either concatenated or overlapping

30   sequentially;

31   (f)   driving each of said energy sources using one of its associated sweep

32   sequences thereby generating a seismic signal which propagates into the

33   earth;

34   (g)   recording uncorrelated seismic data resulting from reflection of said

35   seismic signal from subterranean geologic formations;

36   (h)   combining the portion of said uncorrelated seismic data recorded during a

37   first sweep segment with said recorded uncorrelated seismic data recorded

38   during a 'listen time,' to form a combined uncorrelated seismic data

39   record;

40   (i)   correlating said combined uncorrelated seismic data record with each of

41   said first sequences to give correlated data associated with each of said

42   energy sources.

1   28.   The method of claim 27 further comprising measuring a level of the generated

2   seismic signal and using said level to adjust an amplitude of each of said other of

3   said cascaded sweep sequences prior to correlating said combined recorded

4   seismic data.

1   29.   The method of claim 27 wherein said sweep segments further comprise a

2   sinusoidal wavetrain having a frequency that either increases monotonically with

3   time or decreases monotonically with time.

1   30.   The method of claim 29 wherein said increase or decrease of said frequency is

2   linear with time.

1   31.   The method of claim 27, wherein said sweep segments further comprise a psuedo-

2   random sweep series.

1   32.   The method of claim 31, wherein said pseudo-random sweep series are phase-

2   rotated by increments chosen by the method of claim 27 (d).

1   33.   A method of seismic surveying using a vibrational seismic energy source

2   activated by sweep signals, the method comprising:

3   (a)   selecting a highest order harmonic that has sufficient strength to cause

4   significant harmonic distortion of a sweep segment that is part of a sweep

5   sequence;

6   (b)   selecting a plurality of sweep segments and initial phase angles for each

7   sweep segment so that substantially all harmonics up to and including said

8   highest order harmonic are suppressed,

9   (c)   generating a first sweep sequence associated with each energy source,

10   said sweep segments being either concatenated or overlapping

11   sequentially;

12   (d)   driving said energy source using the sweep sequence thereby generating a

13   seismic signal which propagates into the earth;

14   (e)   recording uncorrelated seismic data resulting from reflection of said

15   seismic signal from subterranean geologic formations;

16   (f)   combining the portion of said uncorrelated seismic data recorded during a

17   first sweep segment with said recorded uncorrelated seismic data recorded

18   during a 'listen time,' to form a combined uncorrelated seismic data

19   record; and

20   (g)   correlating said combined uncorrelated seismic data record with said

21   sequence to give correlated data.

1   34.   The method of claim 33 wherein selecting said initial phase angles further

2   comprises:

3   (i)   constructing a table with N rows and N columns, where N is the number

4   of sweep segments, each entry $e_{H,M}$ being calculated from the formula

5              $e_{H,M} = hm$ modulo N,

6   where h is the row number and m is the column number;

7   (ii)   selecting a number of columns equal to the number of sources such

8   that the number in the first row of each selected column does not appear

9   again in any selected column before the row H=F+1, where F is the

10   highest order harmonic determined to cause significant crossfeed;

11   (iii)   assigning a selected column to each seismic energy source, the initial

12   phase angle for the hth sweep of that seismic energy source being

13   represented by the number in the hth row of that column multiplied by

14             $2\pi/N$;

1   35.   The method of claim 33 further comprising measuring a level of the generated

2   seismic signal and using said level to adjust an amplitude of each of said other of

3   said cascaded sweep sequences prior to correlating said combined recorded

4   seismic data.

1   36.   The method of claim 33 wherein said sweep segment further comprises a

2   sinusoidal wavetrain having a frequency that either increases monotonically with

3   time or decreases monotonically with time.

1   37.   The method of claim 36 wherein said increase or decrease of said frequency is

2   linear with time.

1   38.   The method of claim 33, wherein said sweep segments further comprise a psuedo-

2   random sweep series.